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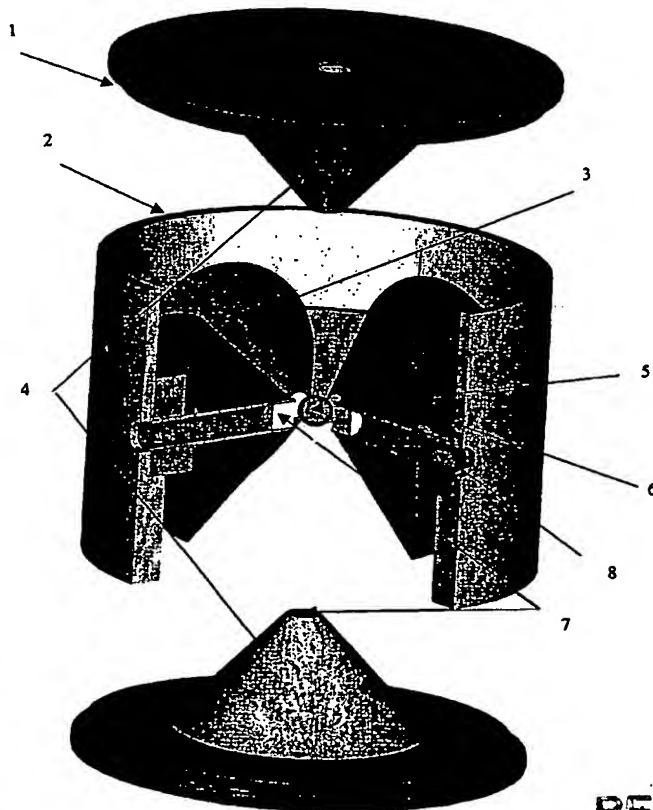
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(54) Title: THREE AXIS ACTIVE MAGNETIC LEVITATION FOR INERTIAL SENSING SYSTEMS



(57) Abstract: The invention relates to an inertial sensor based on the magnetic levitation of an inertial mass comprising an active magnetic bearing unit arranged in such a way as to levitate the inertial mass and characterized by the fact that it furthermore comprises additional active magnetic bearings units arranged in such a way as :- to control the position of said inertial mass along three independent axis. - to create, for any of said independent axis, restoring forces that can be oriented in any of the two directions of said independent axis.

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SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

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Three axis active magnetic levitation for inertial sensing systems

Field of invention

The present invention relates to non-contact inertial sensing systems, that is to say inertial sensors where the inertial mass is never in contact with the rest
5 of the instrument. The contact less suspension of said mass is assured by magnetic bearings.

Background of invention

Current inertial sensing systems such as seismometers, accelerometers,
10 gravimeters and tiltmeters are based on the relative displacement between an inertial mass and the base of the instrument when the said base is subject to an external disturbance (vibration, modification of the "g" level, angle); and gyroscopes, which are another kind of inertial sensing systems, are made of an inertial mass which is rotated about one of its axis of inertia and the
15 measurement principle relies on the relative movement between the said axis and the base of the instrument, or on the force generated by the said axis on the base of the instrument, when the said base is subject to an external movement.

All those inertial sensing systems will be limited by the friction between the
20 inertial mass and the base of the instrument.

Indeed this friction will be responsible of imprecisions in the measurements, of wear between the mechanical parts in contact and it might also lead to failure due to mechanical fatigue.

In addition, inertial sensing systems, such as seismometers in seismology or
25 inclinometers in civil engineering, are often placed to monitor structures or machines and the power consumption of such systems is sometimes a critical factor.

In seismology, it is relevant to study seismic waves within the following
30 ranges:

- Frequencies: From 1mHz to 100Hz
- Accelerations : From 1 nano g to 5 g

Given this wide spread both of the relevant frequencies and the relevant accelerations that have to be recorded and analyzed, several classes of measuring instruments have been developed :

5

- Short Period seismic sensors
- Long Period seismic sensor
- Broad band seismic sensors
- Very broad band seismic sensor

10

All the corresponding products presently commercialized are designed around a damped mechanical mass-spring system made up of a mass detector linked both to a damping mechanism and, with a spring, to the frame of the instrument.

15

In the case of a seismic excitation, the frame of the seismometer follows the ground movement while the mass used as a detector, which we shall designate as the seismic mass, tends to remain in its initial position, thus moving relatively to the frame.

20

In the process the length of the spring changes and the displacement in relation to the frame can be measured as a function of time.

25

The response to a seismic excitation of instruments built according to this principle solely derives from the mechanical characteristics of such a damped spring mass system, i.e. the elastic constant k of the spring and the damping constant d .

30

Since, however, the spring characteristic k is not precisely constant upon the whole range of possible spring deformations, and is temperature dependant, some of the most recent seismometers are equipped with an electromagnetic counterforce system fed by a feed back loop, limiting spring deformations within a small range where k is assimilated to a constant value.

This design, however, does not eliminate distortions caused by spring inertia and friction and, for a given instrument, it is not possible to change its parameters k and d , a fact which limits its use to a chosen range of accelerations and frequencies.

5

In order to eliminate these shortcomings, some new designs have been recently patented: they use either magnetic or electrostatic forces or the force resulting from a special property of a super-conducting loop, called the Meissner effect, in order to levitate a seismic mass.

10 The levitation is obtained through the action of one or several retroactive loops commanded by optical or capacitive sensors measuring the movements of the seismic mass in relation to the frame of the instrument.

Today's high quality seismometers are based on expensive multi-axis spring-damper elements with complex compensation systems. Electrostatic levitation
15 of large spheres in high vacuum is the principle of some high precision gyroscopes.

A three axis active magnetic suspension seismometer, described in the U.S. Patent No 5,565,665 issued to Biglari et al., shows a limited sensitivity,
20 caused by the sensing system, and a non-symmetric behavior of the vertical axis. In addition an upward acceleration can not be counter balanced since there are no electromagnets placed below the seismic mass.

25 In U.S. Patent No 4,947,067 issued to Habermann et al., a three axis magnetic suspension is presented but for the purpose of a vibrator/dampener and not for the purpose of an inertial sensor.

In U.S. Patent No 5,024,088 issued to Komatsu et al., the described
30 accelerometer shows a complex inertial mass and a non optimal arrangement of the coils resulting in a hyperstatic system.

Magnetic suspension and rotation of small spheres was done by J. Beams, but with only one controlled axis and the purpose was to create high centrifugal fields.

5 Other prior art references :

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Summary of the invention

The present invention is based on the magnetic levitation of a inertial mass to create high sensitive non-contact inertial sensing systems.

It relates to an inertial sensor as defined in claim 1.

5 Preferred embodiments are defined in the dependent claims.

The following detailed description will better show all the advantages provided by the invention over the prior art sensors.

Brief description of the drawings

10 For a greater understanding of the nature and objects of the invention, reference should be made to the following detailed description and the accompanying drawings, in which:

15 Figure 1 shows complete view of the first embodiment of the inertial sensing system with:

- 1) End cap
- 2) Support structure
- 3) Horizontal pair of electromagnets
- 4) Vertical pair of electromagnets
- 20 5) Ferromagnetic inertial mass
- 6) Holding structure for the horizontal electromagnets
- 7) High precision position sensors
- 8) Coil armature

25 Figure 2 shows a horizontal cut (O,X,Y) of the first embodiment of the inertial sensing system with:

- 3a), 3b), 3c), 3d) Coils
- 7a), 7b), 7c), 7d) High precision position sensors

30 Figure 3 shows a vertical cut (O,Y,Z) of the first embodiment of the inertial sensing system.

Figure 4 shows a variant of the electromagnets used in the first embodiment with:

- 35 1) Coil
- 2) Laminated ferromagnetic core
- 3) Position sensor
- 4) Inertial mass

Figure 5 shows the second embodiment of the inertial sensing system with:

- 5 1) Upper set of electromagnets (3 coils)
- 2) Lower set of electromagnets (3 coils)
- 3) Position sensing system holder

Figure 6 shows the second embodiment of the inertial sensing system without the position sensing system with:

- 10 1a), 1b), 1c), 2a), 2b), 2c) Coils
- 4) Inertial mass
- 5) Magnetic permeable cores

Figure 7 shows the position sensing system of the second embodiment of the inertial sensing system and its inertial mass with:

- 15 6a) Laser diode 1
- 6b) 4 segments photodiode 1
- 7a) Laser diode 2
- 7b) 4 segments photodiode 2

20 Detailed description of the invention

Implementation 1a (Fig. 1, Fig. 2, Fig. 3)

25 Six electromagnets 3, 4, 3a, 3b, 3c, 3d are diametrically disposed in pairs along three orthogonal axis.

A small size ferromagnetic inertial mass 5 is levitated and its position controlled along three axis.

30 In this first embodiment (Fig. 4), the outside frame 4 is an empty cylinder of homogeneous ferromagnetic material.

By convention, we shall call O its center of gravity and Oz its axis.

Also by convention we shall call Ox and Oy two axis located in the plane perpendicular to Oz and containing O, Oxyz being a direct trihedral.

In this first embodiment the inertial mass 5 is a spherical or cylindrical body of homogeneous ferromagnetic material.

When it is in its original position, the center of this inertial mass is located in O.

5

Circular covers or end caps 1 made of the same ferromagnetic material close both ends of the cylindrical outside frame 2.

Therefore the volume inside the frame 2 of this device (inner volume), is fully protected from any measurement bias caused by changes of outside magnetic conditions.

Seals between the cylinder frame 2 and its covers 1 close hermetically this inner volume which is equipped with a port (not represented in the figure) in order to be put under vacuum whenever necessary for eliminating any bias due to atmospheric convection and friction.

Centered respectively on the Ox and Oy and located symmetrically with regard to point O, two sets of coils 3a, 3b and 3c, 3d, each set made of two symmetrical coils 3 facing each other create opposed magnetic fields.

Inside each coil 3, 4, 3a, 3b, 3c, 3d, at its inner end, an axial sensor 7 (inductive, optical or capacitive), centered on axis Ox or Oy and very rigorously positioned at pre-set distance from the Oz axis, provides instant and highly accurate measurements ($< \mu\text{m}$) of its distance to the inertial mass 5 along Ox or Oy as a function of time.

The two measurement values given by the set of sensors centered, for example, on Ox, provide the basis for a differential measurement of the displacement of the inertial mass 5 along the Ox axis and the same can be said for the set centered on Oy.

A third set of two coils 4 with their corresponding axial sensors 7 is centered on the Oz axis and both coils are located in rigorously symmetrical positions with regards to O.

It operates exactly like the two other sets 3 described above.

5

The following considerations are also applied to implementation 1b and implementation 2:

10 - The distance to the inertial mass of each sensor is sent in the form of a variable tension signal which, in order to remove any unwanted residual noise, is fed to a filtering module.

- The filtered signal is then converted to digital values in an AD converter and the information is multiplexed and processed in a digital controller.

15

- The digital controller:

1°) Calculates the displacement of the inertial mass as time functions measured along the axis Ox, Oy and Oz.

20

2°) Calculates the counterbalancing force necessary in order to bring the inertial mass back to its initial position, with its center in O, thus insuring its levitation.

25 3°) Sends the necessary instructions to a feedback loop commanding the current to the corresponding coils.

4°) Calculates the value of the time function representing the external disturbance from the knowledge of the time functions representing the displacement of the inertial mass and the counterforce applied to it.

30

5°) If this inertial sensing system is used as a seismometer, initial conditions being known, this information can be also taken by the digital controller to

calculate both the speed of the seismic wave and the corresponding ground movements as a function of time.

- 5 - A magnet can be introduced in the electromagnet which is supporting the weight of the inertial mass, in order to compensate it. Therefore power consumption can be reduced.
- A lock-in amplifier can be added to the filtering module in order to increase the signal to noise ratio for low frequencies

10

Implementation 1b (Fig. 4)

The implementation 1b is equivalent to implementation 1a, except for the shape of the six electromagnets. The six electromagnets considered in this
15 implementation have a horseshoe shape (Fig. 4) in order to have less magnetic losses than the electromagnets described in implementation 1a.

Implementation 2 (Fig. 5, Fig. 6, Fig. 7)

As for implementation 1a, a magnetic levitation of a spherical or cylindrical
20 inertial mass 4 is performed with three degrees of freedom control. Six vertically arranged electromagnets 1, 2 create opposing forces in three orthogonal directions. Magnetic permeable cores 5 bring the magnetic field near the inertial mass 4, reducing magnetic losses. The position sensing system is composed of two laser diodes 6a, 7a and two 4-segments
25 photodiodes 6b, 7b orthogonally placed in a horizontal plane between the upper electromagnets 1 and the lower electromagnets 2. Therefore, positions x, y, z of the inertial mass 4 can be measured. Afterwards, the x, y positions are rotated by 45 degrees, filtered and fed back to a digital controller as well as the z position.

30 Horizontal arrangement of the electromagnets 1b, 1c, 2b and 2c (same plane of the sensing system) could be a variant for this implementation.

In order to spin the inertial mass 4, a motor function can be added to the device by superposing a two-phase sinusoidal or square signal to the control current of the electromagnets 1b, 1c, 2b and 2c.

5 Advantages of the present invention

The invention proposed has a symmetrical behavior along three axis, therefore external disturbances in three orthogonal directions can be detected. Since the inertial mass is magnetically levitated with active control,
10 parameters like stiffness and damping can be varied over a large range in order to adjust the natural frequency. Moreover when this inertial sensing system is used as a seismometer, we can even define precisely triggers that characterize the limits between the borders of different seismic events and this way the sensors can vary its damping and spring constant according to
15 the nature of the seismic event.

This design can be made very compact thanks to the use of only one single sensor.

Thanks to differential measurements the precision of the measurements is high and not affected by temperature variation

20 Both position signals and current signals can be used to determine the external disturbance.

Moreover, the whole device is magnetically shielded and thus not affected by ambient magnetic waves.

If we apply the vacuum inside the system, we can avoid the disturbance of the
25 buoyancy forces and enhance the precision of the measurements.

The addition of the motor function will transform the device in a gyroscope.

Applications

30 This invention can be used as an accelerometer, a gravimeter, a tiltmeter or a seismometer. With the addition of the motor function one can use it as a

gyroscope. Application fields are seismology, inertial navigation, structural monitoring and geology.

Claims

5

1. Inertial sensor based on the magnetic levitation of an inertial mass comprising an active magnetic bearing unit arranged in such a way as to levitate the inertial mass and characterized by the fact that it furthermore comprises additional active magnetic bearings units arranged in such a way as :
 - to control the position of said inertial mass along three independent axis.
 - to create, for any of said independent axis, restoring forces that can be oriented in any of the two directions of said independent axis.
- 15 2. Inertial sensor according to claim 1 wherein said inertial mass is a spherical or cylindrical ferromagnetic body.
3. Inertial sensor according to claim 2 comprising:
 - 20 - 6 electromagnets diametrically disposed in pairs along three orthogonal axis,
 - 6 position sensors diametrically disposed in pairs along three orthogonal axis,wherein said pair of electromagnets constitutes each of said active magnetic bearing units,
 - 25 wherein position of said inertial mass is computed differentially with said pairs of position sensors,
 - wherein said inertial sensor is enclosed in an outside frame made of homogeneous ferromagnetic material; said outside frame constituting a magnetic shielding of said inertial sensor,
 - 30 wherein a lock-in amplifier is used for the signal conditioning of said position sensors,

wherein said outer frame of said inertial sensor is hermetically sealed in order to offer the possibility of creating and keeping vacuum inside said frame of said inertial sensor.

5 4. Inertial sensor according to claim 2 comprising:

- 6 vertically arranged electromagnets placed in such a way as to create forces in three orthogonal directions,
- magnetic permeable cores used to bring the magnetic field near the inertial mass and reducing magnetic losses.
- 10 - a position sensing system composed of two laser diodes and two 4-segments photodiodes orthogonally placed in a horizontal plane between the upper said electromagnets and the lower said electromagnets;
wherein the said six vertically arranged electromagnets constitutes said
15 active magnetic bearing units;
wherein position of said inertial mass is computed differentially with said position sensing system;
wherein said inertial sensor is enclosed in an outside frame made of homogeneous ferromagnetic material; said outside frame constituting a
20 magnetic shielding of said inertial sensor;
wherein a lock-in amplifier is used for the signal conditioning of said position sensors.
wherein said outer frame of said inertial sensor is hermetically sealed in order to offer the possibility of creating and keeping vacuum inside said
25 frame of said inertial sensor.

5. Inertial sensor according to claim 2 comprising:

- 4 horizontally arranged electromagnets, placed in such a way as to create forces in two orthogonal directions.
- 30 - 2 vertically arranged electromagnets placed in such a way as to create forces in a direction independent of previously said two orthogonal directions.
- magnetic permeable cores used to bring the magnetic field near the inertial mass and reducing magnetic losses.

- a position sensing system composed of two laser diodes and two 4-segments photodiodes orthogonally placed in a horizontal plane between the upper electromagnet and the lower electromagnet, wherein said horizontally and vertically arranged electromagnets constitutes said active magnetic bearing units;
5 wherein position of said inertial mass is computed differentially with said position sensing system;
wherein said inertial sensor is enclosed in an outside frame made of homogeneous ferromagnetic material; said outside frame constituting a
10 magnetic shielding of said inertial sensor;
wherein a lock-in amplifier can be used for the signal conditioning of said position sensors.
wherein said outer frame of said inertial sensor is hermetically sealed in order to offer the possibility of creating and keeping vacuum inside said
15 frame of said inertial sensor.
6. Inertial sensor according to any of the previous claims with a compensating magnet placed above said inertial mass so as to compensate for the weight of said inertial ferromagnetic mass
20 and to lower the power consumption of said inertial sensor.
7. Use of an inertial sensor according to any of the previous claims as a three dimensional non-contact accelerometer or as a three dimensional non-contact seismometer.
25
8. Use of an inertial sensor according to any of the previous claims 1 to 6 as a three dimensional non-contact or tiltmeter (inclinometer).
9. Use of an inertial sensor according to any of the previous claims 1 to 6
30 comprising a motor function implemented by applying a rotating magnetic field to, at least, two of said electromagnetic bearing units in order to spin said inertial mass around its main axis of inertia.

10. Use of an inertial sensor according to the previous claim as a non-contact gyroscope.

5 11. Use of an inertial sensor according to any of claims 1 to 6 as a non contact gravimeter.

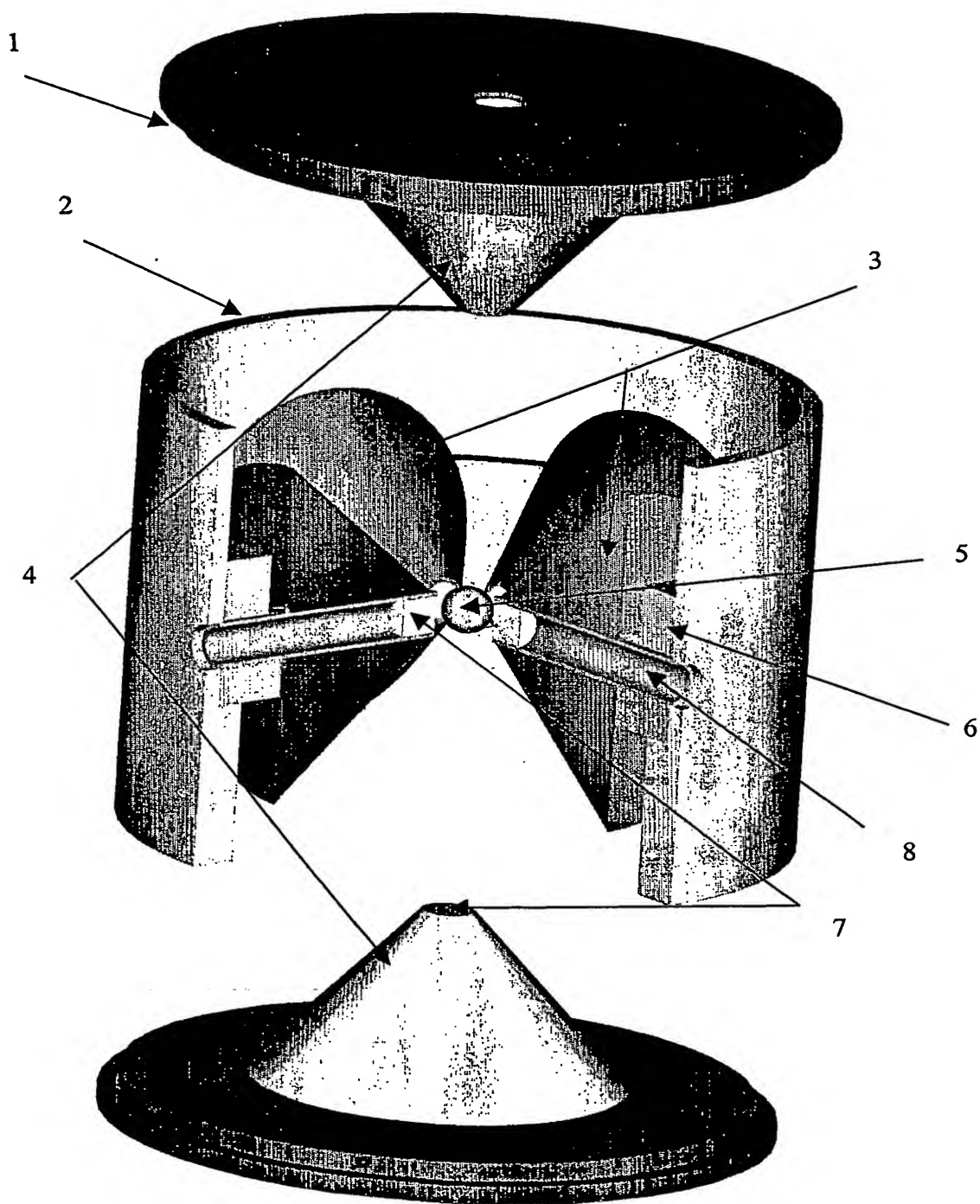


Figure 1 BEST AVAILABLE COPY

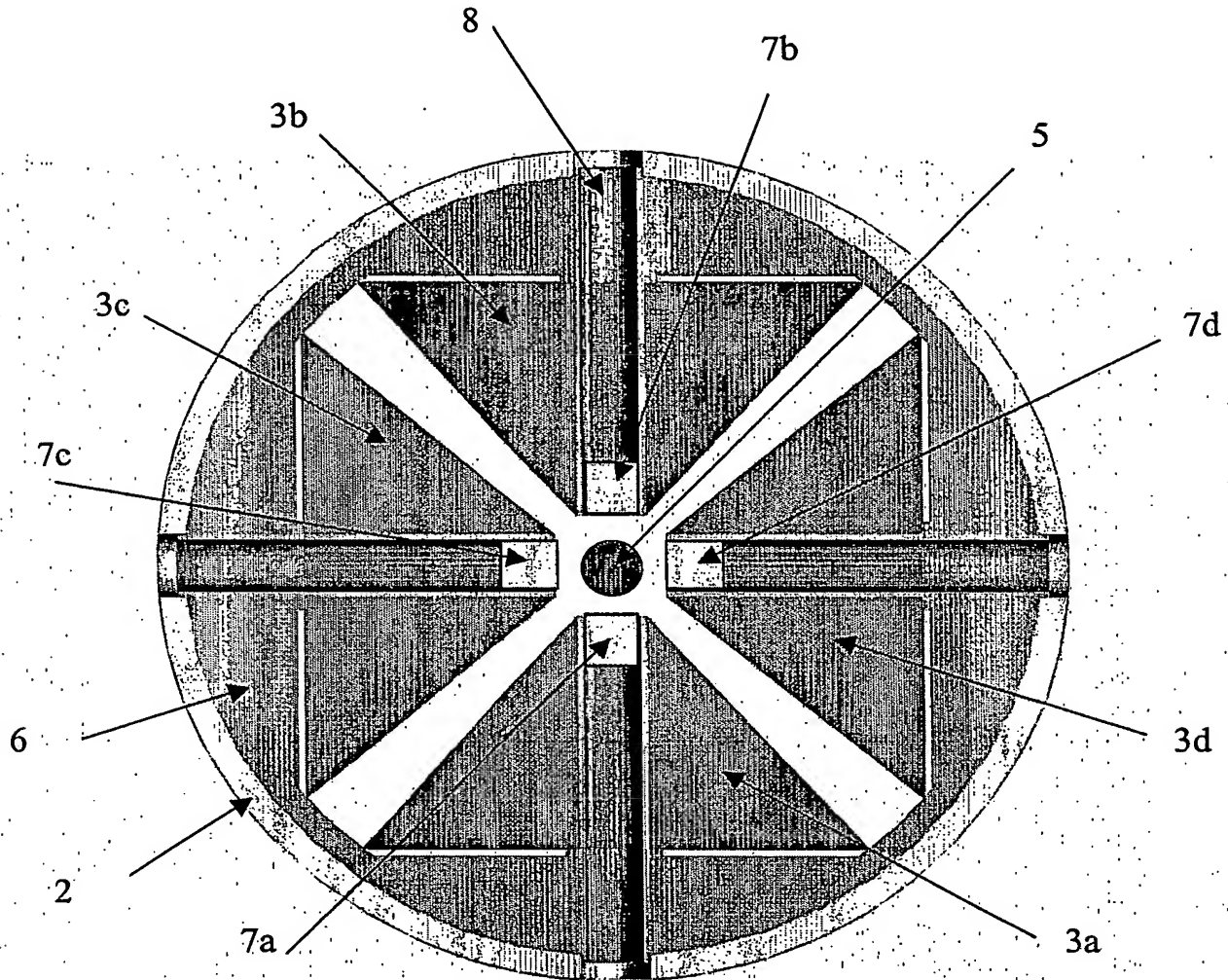


Figure 2

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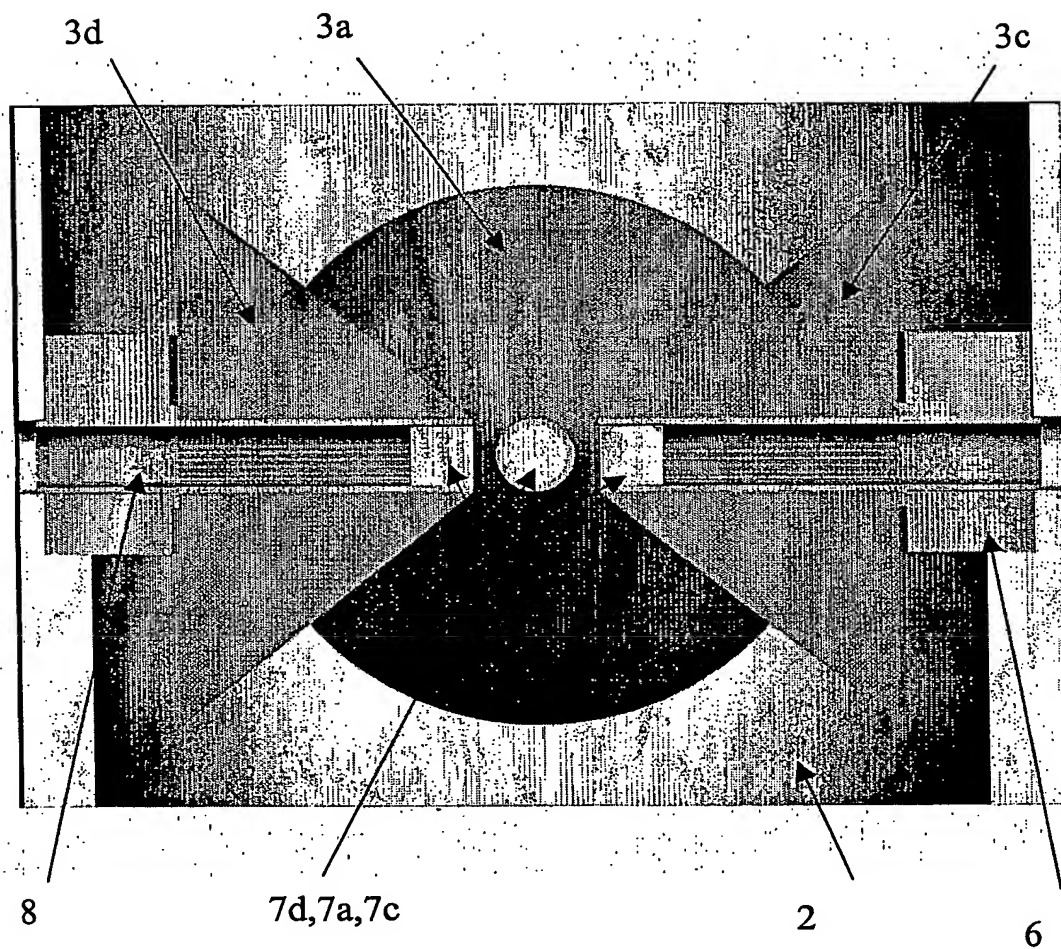


Figure 3

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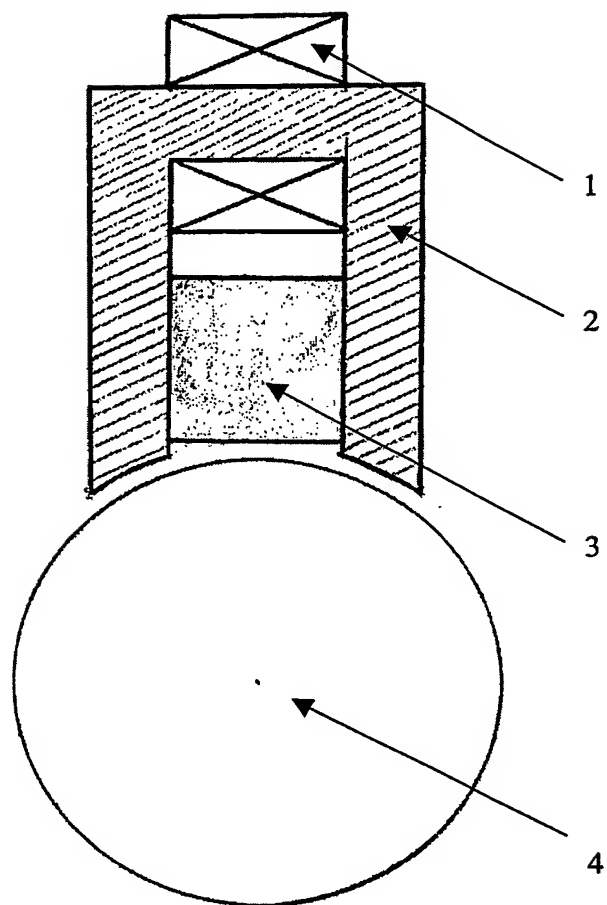


Figure 4

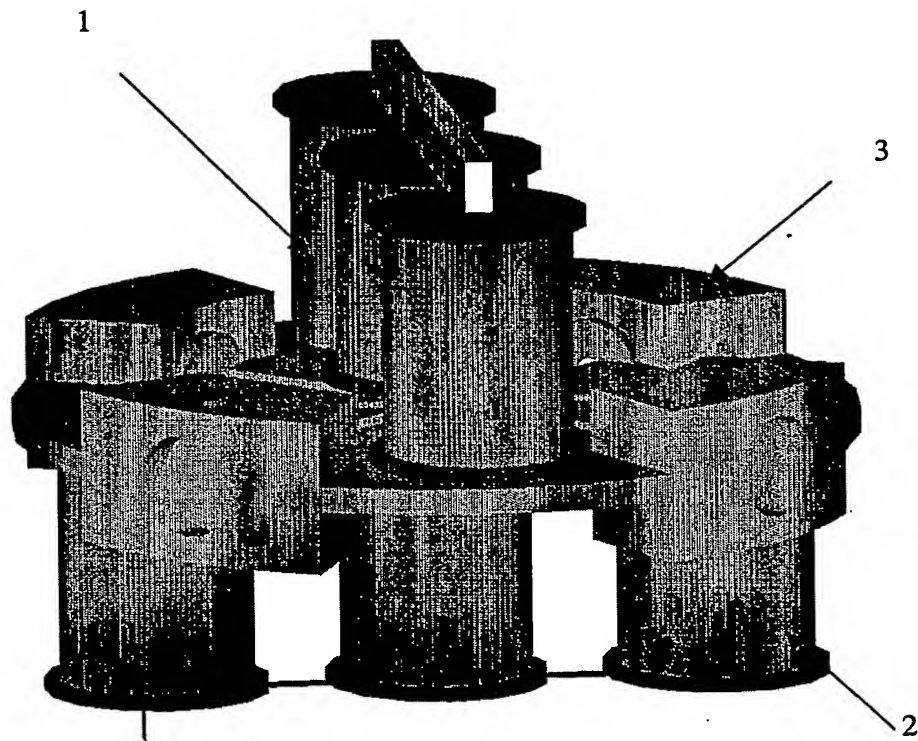


Figure 5

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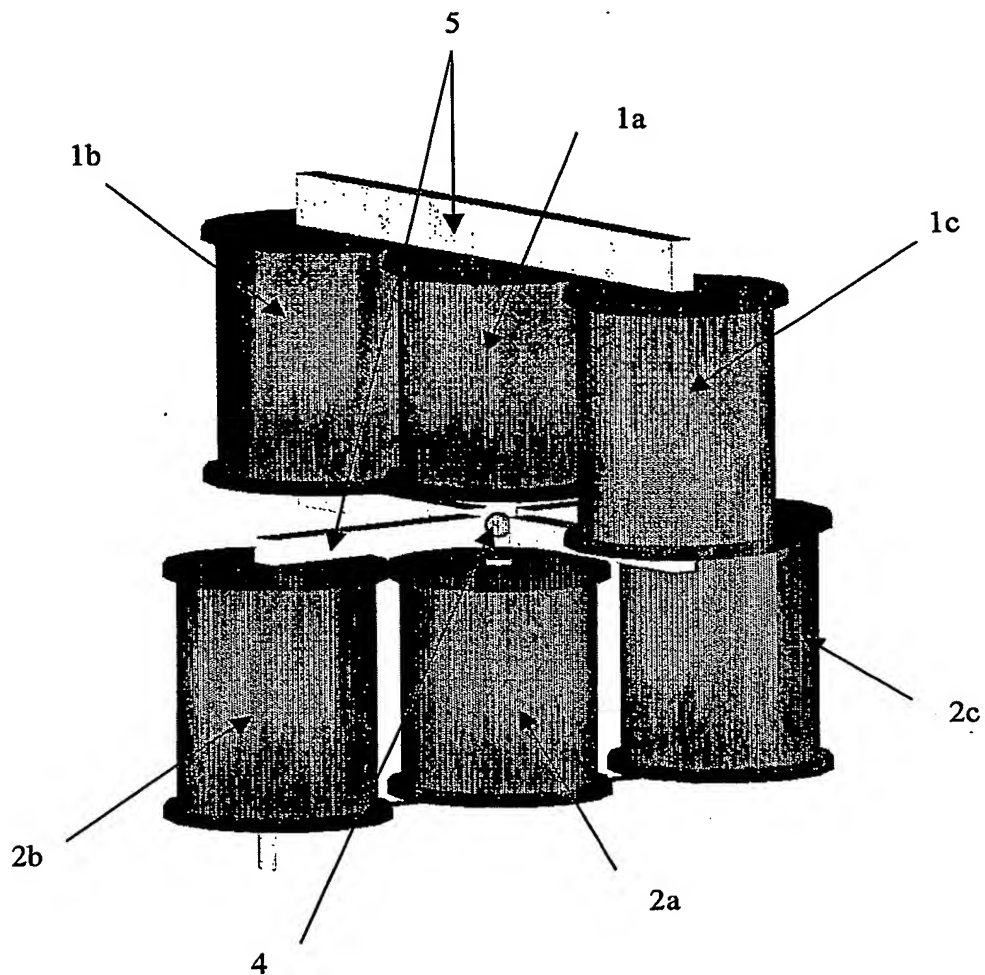


Figure 6

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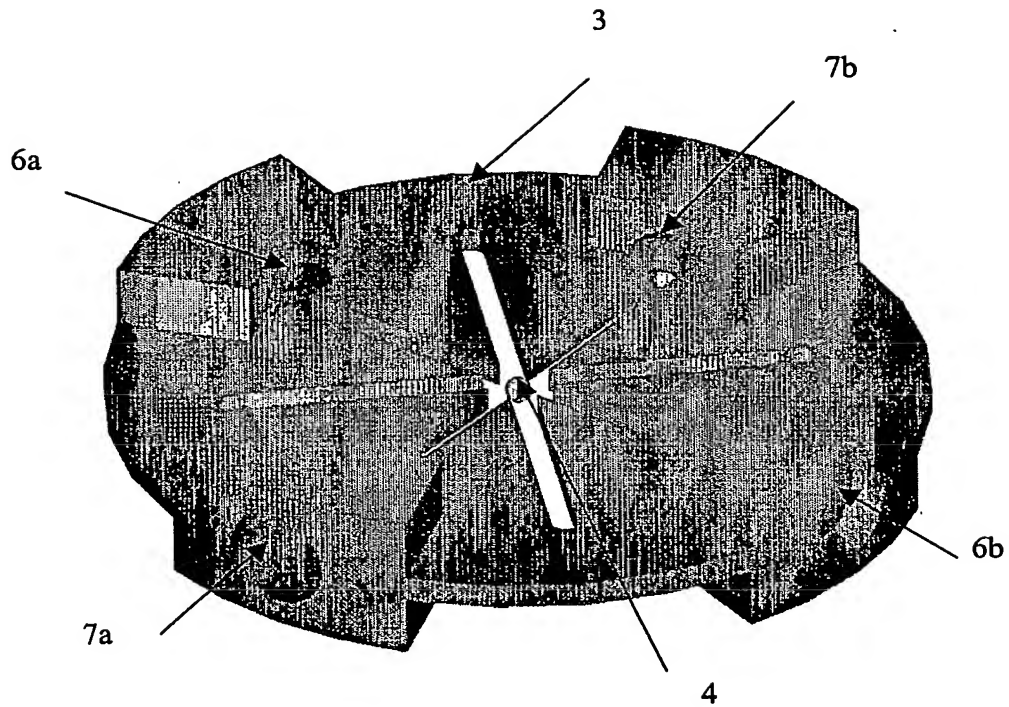


Figure 7

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INTERNATIONAL SEARCH REPORT

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PCT/CH 0597

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 G01P15/00 G01P15/13 G01P15/08 G01C19/24 G01V1/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G01P G01C G01V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the International search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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X	US 2 919 583 A (PARKER HERMON M) 5 January 1960 (1960-01-05) column 1, line 18 - line 18; figure 2 column 3, line 42 - line 47 column 4, line 22 - line 36; claim 1	1-6,9,10
X	US 3 491 600 A (KASPARIAN MALCOLM JR) 27 January 1970 (1970-01-27) abstract; figure 1 column 3, line 31 - line 49 column 4, line 43 - line 46 column 4, line 73 - line 74 column 7, line 22 - line 27 column 7, line 44 - line 49	1-7

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☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	<p>EP 1 077 379 A (IWAKI ELECTRONICS CO LTD)</p> <p>21 February 2001 (2001-02-21)</p> <p>column 9, line 8 - line 16; claim 3</p> <p>column 12, line 35 - line 45</p> <p>column 14, line 37 - line 47; figures 13,14</p> <p>-----</p>	1-11

INTERNATIONAL SEARCH REPORT

Information on patent family members

International

Publication No

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